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1. Introduction

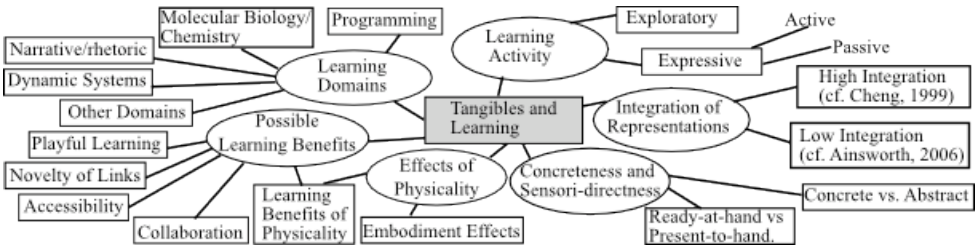
Tangible user interfaces (TUI) represent an increasingly popular approach to the design of systems for a variety of application domains including learning, collaborative planning and play. To date, most research has focused on technological development and the construction of descriptive taxonomies [e.g. 3, 4, 14]. A range of novel links between physical activity and digital effects has been explored together with developing a lingua franca to categorize and compare these systems. However, as with much of the early work on graphical interfaces [see 12], empirical work and theoretical development have failed to keep up with the pace of technical development in this area. While there have been some attempts to link tangible interaction with philosophical phenomenology [2], theoretical underpinnings of the learning and other cognitive benefits of TUIs, that have been empirically tested, are distinctly lacking. While there are many claims made about the benefits of tangibles compared with other kinds of interfaces (e.g., GUIs, speech) we really do not know why, how or whether they can be substantiated. The user studies that have been carried out have been largely informal evaluations that tend to be positive, i.e., users like them and find them easy to use. However, the results from the few controlled experiments that have been carried out have revealed no difference in performance between GUIs and TUIs [see 8]. This begs the question of what is actually gained from having physical, familiar and manipulative artefacts that are closely coupled with different kinds of digital information.

We argue that theoretically-grounded accounts and empirically-based studies are now needed to understand better how tangible interfaces actually work. These should explicate the cognitive and/or social effects of using tangibles; whether or why tangible interfaces might promote interactive benefits, which features of tangible interface designs might be associated with these benefits and in which situations. In this paper, we present an overview of the work beginning to be carried out in our laboratory, which aims to put our understanding of tangible interfaces on a firmer theoretical footing. This work has three strands. The first strand is an analytic framework [8], derived from an analysis of the literature in cognitive science, tangible computing and education, designed to support the design of tangible interfaces for learning. A number of latent trends are highlighted, providing theoretically motivated categorizations of activity with tangible systems. The second strand is a program of comparative empirical work that is investigating the potential of a variety of shareable interfaces to support different aspects of collaborative activities across a number of representative collaborative tasks [e.g., 11]. 'Shareable interfaces' is a generic term that refers to technologies that are specifically designed to enable collocated groups to work on shared representations [12]. They include systems with multiple input devices, interactive touch surfaces and tangible interfaces. The third strand of our research is applying our conceptual framework on tangible interaction [5] to the analysis of existing systems, with the aim of informing field studies, and in design projects. The goal is to develop a practical application of the framework that can be communicated effectively to the design community. Together, the three strands provide an approach to systematically progress research into tangible interfaces that is theoretically, empirically and practically grounded. It will also provide a body of empirical evidence that can support or challenge the claims and assumptions made about how TUIs work.

For the remainder of the paper we briefly describe how we are addressing two fundamental research questions that are considered central to our agenda: (i) how can tangible interfaces facilitate learning and (ii) how do shareable interfaces support more equitable participation in group settings?

2. How Can We Determine if Tangible Interfaces Facilitate Learning?

An area that has received much interest from tangible interface designers is learning [e.g., 10]. This interest is related to the more common view within education that hands-on activity or manipulation of physical artefacts can be of particular educational benefit. However, theory and empirical demonstrations of the utility of tangible interfaces for learning have been less forthcoming. This has led to a situation where designers of learning environments have little principled basis on which to decide whether a tangible interface will be suitable for a particular task, which of the many categories of interface might be most appropriate, what features of a design might be associated with particular benefits to interaction or learning and what features might be more incidental. They must therefore rely upon intuitions about physical interaction, an approach that has been criticized as potentially leading to incorrect assumptions [1]. Here we begin to outline the dimensions, variables and research questions that need to be empirically addressed.



The figure above shows a conceptual framework that makes explicit all the various factors that can influence whether and how tangible interfaces might support learning [8]. The framework is derived from an analysis of the research and our initial experiments on tangible interfaces and learning with physical materials. It outlines six major themes that need empirical testing and further theoretical development. These are:

(i) Possible learning benefits

Based on our critique of the literature, a number of possible learning benefits of interacting with tangible interfaces have been suggested but not tested. These are:

• *Learning benefits of physicality* – there might be a close link between physical activity and cognition that can facilitate some forms of cognition
• *Collaboration* – shared spaces can allow users to readily monitor each others' gaze; increase the visibility of actions; facilitate increased awareness and situated learning; provide multiple access points for effective turn-taking; and enable users to manipulate physical artefacts outside the interactive space to help social organisation and planning.
• *Accessibility* – it is possible that tangible interfaces are more intuitive or accessible, particularly for young children
• *Novelty of links* – the novelty of coupling physical activity with digital effects may increase reflection in children
• *Playful learning* – interacting with various physical artefacts can increase the playfulness of learning

(ii) Learning domains

A number of learning domains have been supported by tangible interface designs, most notably *programming, narrative, molecular biology/chemistry* and *dynamic systems*. A commonality of these interfaces is that they are inherently spatial, either literally in the case of the physical configuration of molecules, or metaphorically in terms of the representational systems typically used to represent the domains, which often utilise two-dimensional spatial representations. A research question that still needs addressing is what benefit is gained through the physical manipulation of these types of representations compared with the manipulation of equivalent graphical objects on a display.

(iii) Learning activity

Two different types of learning activity that lend themselves to being supported and dovetailed between by tangible interfaces are exploratory and expressive activities [9].

• *Exploratory activity* - involves the learner exploring an existing representation or model of a topic, typically based on the ideas of a teacher or domain expert. Tangibles might be particularly suitable for this type of learning if they are found to be more natural or intuitive than other kinds of interface, or if the structure of the physical apparatus might influence or constrain the interpretations made by the students.

• *Expressive activity* - involves the creation of an external representation of a domain. This can also include system-generated representations created through learners' interaction with the system. Externalizing ideas in this way might facilitate reflective thought. Tangibles might also allow learners to create constructions that might not be possible in other media.

(iv) Integration and representation

Taxonomic work on tangibles has highlighted the level of integration between the physical and digital representations in tangible interfaces as an important distinction. Integration here refers to spatial and temporal contiguity. However, there is little support yet in the literature for the cognitive effects of interacting with a highly integrated system or one with low integration between physical and digital representations.

(v) Concreteness and sensori-directness

When considering the benefits of interacting with physical materials in learning, the effects of the concreteness are often conflated with the physicality of the materials. We suggest that concreteness effects should be treated separately.

• *Concrete vs. abstract* Both types of materials can be of benefit to learning, e.g., while concrete materials can lead to better task performance, abstract materials can lead to better knowledge transfer. Increase abstractness can lead to greater reflection and planning. The question of what combination of concrete and abstract materials should be used in tangible interface design remains an empirical question.

• *Ready-at-hand vs. present –to-hand* Attending to both the activity and the tool or object as an object of inquiry are considered desirable and which tangible interfaces could effectively support. While engaged activity is important for learning so too are periods of disengaged reflection.

(vi) Effects of physicality

Research in cognitive science focusing on embodiment argues for a close link between physical activity and cognition. A second body of literature in education emphasises the role of physical manipulative materials in supporting learning. However, there have been few empirical comparisons of learners working with physical and graphical materials. Those that have been carried out have found no learning benefits of interacting with physical materials.

3. How Can Shareable Interfaces Enable More Equitable Participation in Group Settings?

A key question we are investigating is whether shareable interfaces encourage more equitable participation from group members – given that they are inherently designed to support collaboration. We have conducted an initial study comparing different types of shareable interfaces with a control condition of a single user interface (PC with one mouse input). These were a multi-user tabletop and a tangibles condition. Our different designs were informed by an adapted version of a cognitive framework of entry points [6, 7]. By an entry point is meant a structure or cue that represents an invitation to enter an environment, such as an information space or a physical office. It is an abstract concept intended to characterize the context of work in terms of a user's perception of the state of various digital and physical resources. Entry points can encourage or inhibit a person towards entering physical or digital spaces and acting upon something as a function of its current state.

Using the entry points framework, we systematically designed and configured different kinds of shareable interfaces for co-located groups to vary in terms of how they invite group members to enter at various points at appropriate times. These ranged from most to least constrained. Our hypothesis was that the more inviting (i.e., least constrained) a shareable interface is the more likely that equitable participation will ensue. Findings from an initial experiment, where 6 groups of 3 participants for each condition took part in a collaborative design task showed significant differences between the conditions. Surprisingly, the greatest number of utterances and suggestions made was in the most constrained condition (i.e., the PC with one input device) but on further inspection it was found that these contributions were made mainly by one person. There was very little switching of roles in terms of who interacted with or created the content using the mouse. In contrast, the least constrained, shareable interfaces encouraged the most equitable physical participation. One interesting finding to emerge was that the non-native English speakers and shy group members, while not verbally contributing as much as the others, spent much more time physically creating and interacting with the design materials. This suggests that the availability of entry points in the tabletop and tangibles conditions provided more opportunities for them to participate in the physical design activity than in the control condition. There wasn't, however, a significant difference between the tangibles and tabletop conditions, although there was a number of differences in terms of turn-taking, social organisation and planning.

We are currently planning a further set of empirical comparisons between different kinds of sharable interfaces – tangible, tabletop and multi-user graphical – for two kinds of collaborative learning activity: an exploratory discovery learning task focussing on the interaction between evolving organisms and the physical environment and an expressive concept mapping task where learners must work together to build up an external representation of their understanding of biological and physical systems. We will aim to test hypotheses based on claims made about the relative benefits of each of these technologies: that the production of gestures and peripheral awareness of others' actions will be increased, that participation will be more equitable and that the physical objects used in tangible interfaces might have an influence on the social organisation of action (cp. [5]). Furthermore, we will determine whether there is variance in the suitability of different sharable interfaces for exploratory and expressive learning tasks. We will also carry out exploratory observational analysis of users' interactions to uncover novel phenomena. The outcome of these studies is intended to build up a corpus of theoretically grounded findings that can systematically guide the design of shareable interfaces for collaborative learning and working.

To conclude, are tangible interfaces really any better than other kinds, such as GUIs, speech or command-based ones for supporting learning and other activities? Intuitively, it just seems the case; and like so many other researchers we can easily come up with a list of putative benefits. However, theoretically and empirically grounded research may prove that these may not be as marked or indeed significant as we assumed them to be. Our hunch is that the real value of tangible interfaces may turn out to be largely in terms of how they can facilitate various kinds of collaborative activities – that are not possible or poorly supported by single user technologies.

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